Universität Rostock
Traditio et Innovatio

INSTITUT FÜR PHYSIK

Investigation of B-meson decays into baryons with the BABAR detector

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Bundesministerium
für Bildung
und Forschung

Why investigate B decays into baryons?

Physics scope

- uncover baryon production mechanisms
- searches for excited baryon resonances
- determination of baryon spins

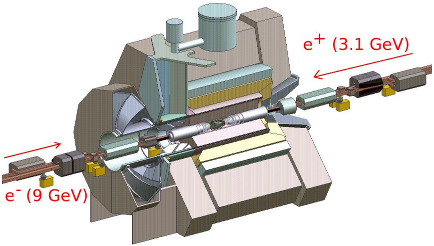
$\Rightarrow$ improved theoretical understanding of baryonic B decays necessary

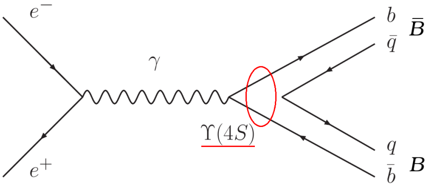
$\mathcal{B}(B \to baryons...) = (6.8 \pm 0.6)\%$

- but: only $1/7$ explicitly known

The *BABAR* experiment

- detector at the PEP-II e^+e^- asymmetric-energy B Factory at SLAC
- operated from 1999 to 2008
- B production in the process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- in total $\approx 470 \times 10^6$ $B\bar{B}$ pairs



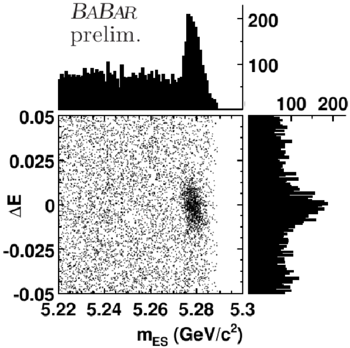


B reconstruction

- $\sqrt{s} = m(\Upsilon(4S))$ exhibits unique situation for the study of rare B decays

$\rightarrow$ two independent variables for signal extraction: $\boldsymbol{m_{\text{ES}}}$ and $\boldsymbol{\Delta E}$

$$\Delta E = \sqrt{s}/2 - E_B$$



$$m_{\text{ES}} = \sqrt{s/4 - \vec{p}_B^{\,2}}$$

- $(E_B, \vec{p}_B)$: 4-vector in CMS
- together with:
  - particle ID
  - event topology
  - kinematic constraints

$\rightarrow$ good separation of signal and combinatoric background

- limited suppression of fake signal (*peaking background*)

$B^- \rightarrow D^0 p\bar{p}\pi^-$ arXiv:0908.2202v1 [hep-ex]

$B \to D^{(*)} p\bar{p}\, m \cdot \pi, \quad m = 0, 1, 2$

arXiv:0908.2202v1 [hep-ex]

- measurement of 10 B meson decays (6 are first observations)
- based on a data set of 455×10^6 $B\bar{B}$ pairs
- branching fraction results are averaged over different $D^{(*)}$ decay modes

$$\bar{B}^0 \to D^0 p\bar{p} = (1.02 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}) \times 10^{-4}$$
$$\bar{B}^0 \to D^+ p\bar{p}\pi^- = (3.32 \pm 0.10_{\text{stat}} \pm 0.27_{\text{syst}}) \times 10^{-4}$$
$$\bar{B}^0 \to D^0 p\bar{p}\pi^-\pi^+ = (2.99 \pm 0.21_{\text{stat}} \pm 0.44_{\text{syst}}) \times 10^{-4}$$
$$\ldots$$

- the high systematic uncertainty arises mainly from peaking background
- ratios of the branching fractions indicate:

$$\mathcal{B}(B \to 3 - body) < \mathcal{B}(B \to 5 - body) < \mathcal{B}(B \to 4 - body)$$

$\bar{B}^0 \to \Lambda_c^+ \overline{p}$ and $B^- \to \Lambda_c^+ \overline{p} \pi^-$ PRD 78, 112003 (2008)

- based on a data set of 383×10^6 $B\bar{B}$ pairs
- branching fraction results are averaged over five Λ_c^+ decay modes

$$\bar{B}^0 \to \Lambda_c^+ \overline{p} = (0.19 \pm 0.02_{\text{stat}} \pm 0.01_{\text{syst}} \pm 0.05_{\Lambda_c^+}) \times 10^{-4}$$
$$B^- \to \Lambda_c^+ \overline{p} \pi^- = (3.38 \pm 0.12_{\text{stat}} \pm 0.12_{\text{syst}} \pm 0.88_{\Lambda_c^+}) \times 10^{-4}$$

- Belle already measured $\bar{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+$ (Physical Review D 75, 011101(R))

$$B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^+ = (11.2 \pm 1.4_{\text{stat+syst}} \pm 2.9_{\Lambda_c^+}) \times 10^{-4}$$
$$B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^+ (\text{nonresonant}) = (6.4 \pm 1.0_{\text{stat+syst}} \pm 1.7_{\Lambda_c^+}) \times 10^{-4}$$

Theoretical/Phenomenological explanation

- no strict theoretical predictions
- several phenomenological ideas are on the market, e.g.
  - Wei-Shu Hou and A. Soni arXiv:hep-ph/0008079v1
  - Mahiko Suzuki arXiv:hep-ph/0609133v3

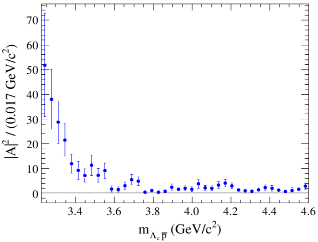
General idea

baryon production favored if baryon and anti-baryon recoil against one or more mesons, leptons

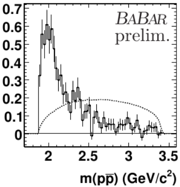
$\Rightarrow$ invariant baryon anti-baryon mass should show an enhancement

Invariant baryon anti-baryon mass

$B^- \to \Lambda_c^+ \bar{p} \pi^-$

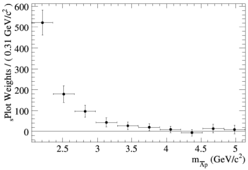


- separation of signal and bkg achieved with the ${}_s\mathcal{P}$lot formalism
  NIM A 555, 356 (2005)
- resulting distribution divided by phase space expectation
- consistent with enhancement seen in other analyses



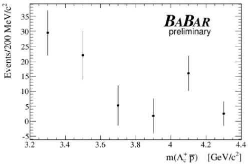
$B \to D^0 p\bar{p}$

arXiv:0908.2202v1 [hep-ex]



$\bar{B}^0 \to \Lambda \bar{p} \pi^-$

PRD 79, 112009 (2009)



$\bar{B}^0 \to \Lambda_c^+ \bar{p} K^- \pi^+$

PRD 80, 051105(R) (2009); PoS(EPS-HEP 2009)215

Resonances

- branching fraction measurements $\rightarrow$ high multiplicities are preferred
- e.g. for $B \rightarrow D^{(*)}p\overline{p}\ m \cdot \pi$:

$$\mathcal{B}(B \rightarrow 3 - body) < \mathcal{B}(B \rightarrow 5 - body) < \mathcal{B}(B \rightarrow 4 - body)$$

- can be explained by threshold enhancement (partly)

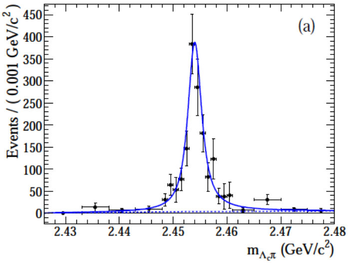
$$B^- \rightarrow \Lambda_c^+ \overline{p} \pi^- = (3.38 \pm 0.12_{\text{stat}} \pm 0.12_{\text{syst}} \pm 0.88_{\Lambda_c^+}) \times 10^{-4}$$

$$B^- \rightarrow \Lambda_c^+ \overline{p} \pi^- \pi^+ = (11.2 \pm 1.4_{\text{stat+syst}} \pm 2.9_{\Lambda_c^+}) \times 10^{-4}$$

$$B^- \rightarrow \Lambda_c^+ \overline{p} \pi^- \pi^+ \text{(nonresonant)} = (6.4 \pm 1.0_{\text{stat+syst}} \pm 1.7_{\Lambda_c^+}) \times 10^{-4}$$

$\rightarrow$ resonant subdecays have to be considered

$\Sigma_c(2455)^0$ in $B^- \to \Lambda_c^+ \overline{p} \pi^-$



- signal and background separated with the ${}_s\mathcal{P}$lot formalism
- fitted with:
  - non-relativistic Breit-Wigner
  - double Gaussian for resolution (parameters fixed)
  - threshold-function for bkg (parameters fixed)

Fit Parameter	*BABAR*	PDG (w/o *BABAR*)
m (GeV/c^2)	2.4540 ± 0.0002	2.4538 ± 0.0002
Γ (MeV)	2.6 ± 0.5	2.2 ± 0.4

- fit results compatible with PDG values
- influence of $B^- \to \Sigma_c^0 \overline{p}$ on $\mathcal{B}(B^- \to \Lambda_c^+ \overline{p} \pi^-)$:

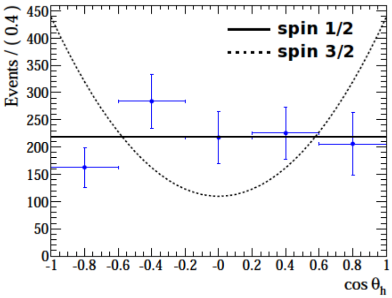
$$\frac{\mathcal{B}(B^- \to \Sigma_c(2455)^0 \overline{p})}{\mathcal{B}(B^- \to \Lambda_c^+ \overline{p} \pi^-)} = (12.3 \pm 1.2_{\text{stat}} \pm 0.8_{\text{syst}}) \times 10^{-2}$$

Spin measurement of $\Sigma_c(2455)^0$

- in the quark model the $\Sigma_c(2455)$ is expected to have spin-$\frac{1}{2}$

$\rightarrow$ helicity analysis of $B^- \rightarrow \Sigma_c(2455)^0\overline{p}$, $\Sigma_c(2455)^0 \rightarrow \Lambda_c^+\pi^-$

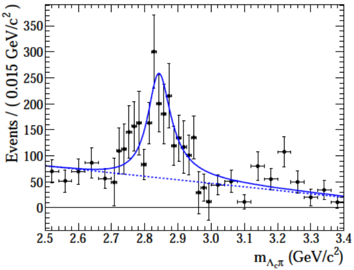
  - helicity angle θ_h between momentum vector of Λ_c^+ and $\overline{p}$ in $\Sigma_c(2455)^0$ rest frame



- distribution consistent with spin-$\frac{1}{2}$ hypothesis
- excludes spin-$\frac{3}{2}$ at $> 4\sigma$ level

$\Sigma_c(2800)$ resonance (?)

- Belle observed a resonance at $2.802\,\mathrm{GeV}/c^2$ in continuum ($e^+e^- \to c\bar{c}$) events
- $B^- \to \Lambda_c^+\bar{p}\pi^-$ analysis found resonance near $2.8\,\mathrm{GeV}/c^2$



Fit Parameter	*BABAR*	Belle
m (GeV/c^2)	2.846 ± 0.008	$2.802^{+0.004}_{-0.007}$
Γ (MeV)	86^{+33}_{-22}	61^{+28}_{-18}

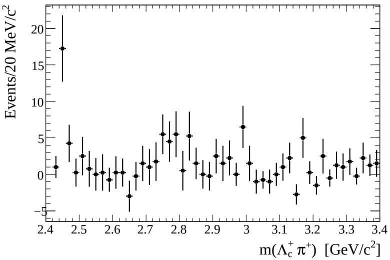
$\rightarrow$ mass differs by 3σ (assuming Gaussian statistics)

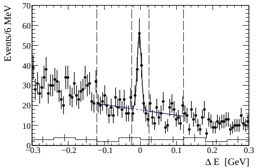
$\Sigma_c(2800)$ resonance(s)

- do we observe an orbitally excited $\Sigma_c(2800)$?

$\rightarrow$ Do we see other mass states as well?

$\bar{B}^0 \rightarrow \Lambda_c^+ \overline{p} K^- \pi^+$ PRD 80, 051105(R) (2009)





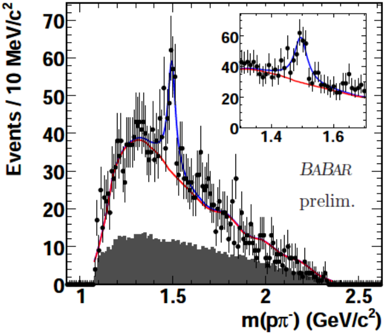
- ΔE sideband subtracted $m(\Lambda_c^+ \pi^+)$ distribution shows:
  - a strong $\Sigma_c(2455)^{++}$ signal
  - an excess near $2.78\,\mathrm{GeV}/c^2$

$\rightarrow$ a lower mass state of the $\Sigma_c(2800)$?

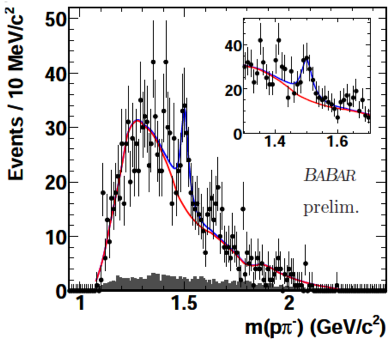
- no conclusive statement can be made here (statistics too low)

New resonance $X(1500)$?

- in $B \to D^{(*)} p\bar{p}\pi^-$ we found a narrow resonance $X(1500)$ in $m(p\pi^-)$



$\bar{B}^0 \to D^+ p\bar{p}\pi^-$

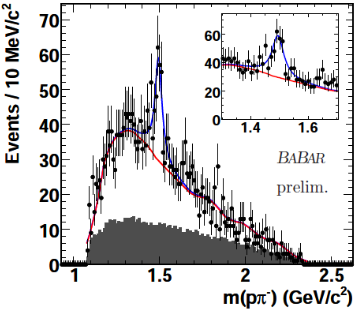


$\bar{B}^0 \to D^{*+} p\bar{p}\pi^-$

- background description taken from $m(\bar{p}\pi^-)$
- signal described by a Breit Wigner
  - $m = (1497.4 \pm 3.0 \pm 0.9)\,\mathrm{MeV}/c^2$
  - $\Gamma = (47 \pm 12 \pm 4)\,\mathrm{MeV}$

Summary

- measurements suggest that high multiplicities are preferred
- spin of the $\Sigma_c(2455)^0$ resonance could be determined to be $1/2$
- possible observation of an orbitally excited $\Sigma_c(2800)$
- possible new baryon resonance $X(1500)$ observed



⇒ baryonic B decays interesting from several points of view

Outlook

- independent confirmation of the baryon resonance $X(1500)$
- further studies of orbitally excited $\Sigma_c(2800)$ states

Ongoing analyses at *BABAR* and Belle and future B factories will investigate the dynamic properties of baryonic B decays

Backup slides

$\mathcal{B}(B \rightarrow baryons\ ...)$

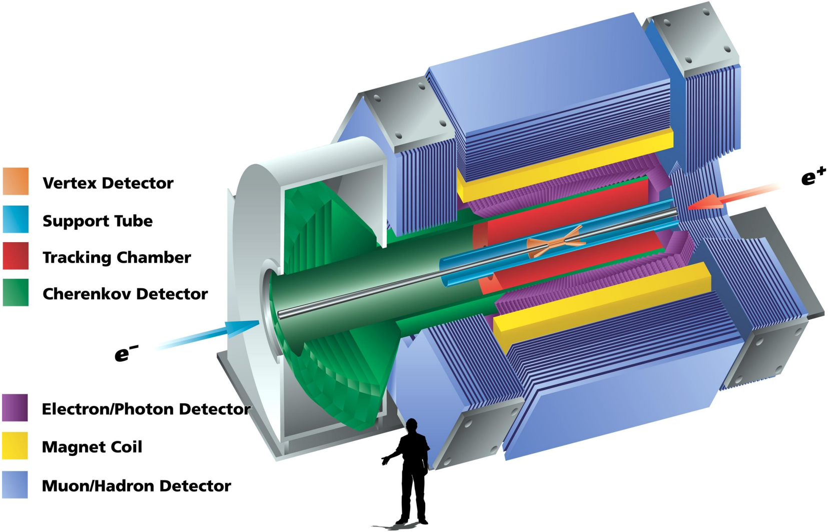
- measured by the ARGUS experiment[2]
- determine number of events with:
  - a reconstructed proton
  - a reconstructed Λ
  - the combination $p\bar{p}$ and Λp
  - various lepton-baryon and lepton-baryon-anti baryon combinations

  $\Rightarrow$ *12 equations with 5 unknowns*
- determine all 5 unknowns by a fit

$$\Rightarrow \mathcal{B}(B \rightarrow baryons\ ...) = (6.8 \pm 0.5_{\text{stat}} \pm 0.3_{\text{syst}})\%$$

2 H. Albrecht et al., ARGUS Koll., Z. Phys. C 56 1 (1992)

The *BABAR* detector



$B \to D^{(*)} p\bar{p}\ m \cdot \pi, \quad m = 0, 1, 2$ arXiv:0908.2202v1 [hep-ex]

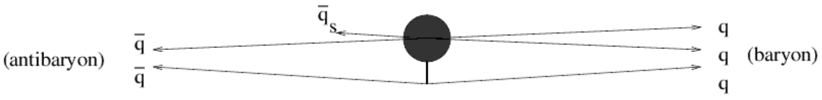
B decay	$\mathcal{B} \pm \sigma_{stat} \pm \sigma_{syst}$ (10^{-4})
$\bar{B}^0 \to D^0 p\bar{p}$	$1.02 \pm 0.04 \pm 0.05$
$\bar{B}^0 \to D^{*0} p\bar{p}$	$0.97 \pm 0.07 \pm 0.09$
$\bar{B}^0 \to D^+ p\bar{p}\pi^-$	$3.32 \pm 0.10 \pm 0.27$
$\bar{B}^0 \to D^{*+} p\bar{p}\pi^-$	$4.55 \pm 0.16 \pm 0.37$
$B^- \to D^0 p\bar{p}\pi^-$	$3.72 \pm 0.11 \pm 0.23$
$B^- \to D^{*0} p\bar{p}\pi^-$	$3.73 \pm 0.17 \pm 0.39$
$\bar{B}^0 \to D^0 p\bar{p}\pi^-\pi^+$	$2.99 \pm 0.21 \pm 0.44$
$\bar{B}^0 \to D^{*0} p\bar{p}\pi^-\pi^+$	$1.91 \pm 0.36 \pm 0.29$
$B^- \to D^+ p\bar{p}\pi^-\pi^-$	$1.66 \pm 0.13 \pm 0.27$
$B^- \to D^{*+} p\bar{p}\pi^-\pi^-$	$1.86 \pm 0.16 \pm 0.18$

$B \to D^{(*)}p\bar{p}\, m\cdot\pi, \quad m = 0, 1, 2$ - systematics

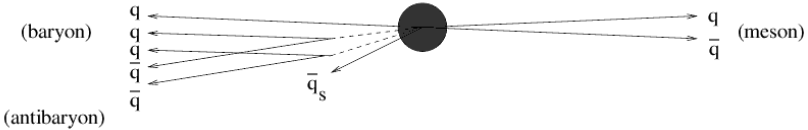
Item	Source description	%of $\mathcal{B}$
I	$B\overline{B}$ counting	1.1
II.1	Branching fraction of $\Upsilon(4S)$	1.6
II.2	Branching fraction of $D \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, $K\pi\pi$	1.8, 4.4, 3.2, 3.6, resp.
II.3	Branching fraction of $D^* \to D^0\pi^0$, $D^0\pi^+$	4.7, 0.7, resp.
III.1	Efficiency of finding charged tracks not including soft pions	0.5 per track
III.2	Efficiency of finding soft charged pions from D^{*+}	3.1 per π
III.3	Efficiency of finding neutral pions	3.0 per π^0
III.4	Efficiency of finding B decays in bins of $m^2(p\overline{p})$ and $m^2(D^{(*)}p)$	0.8 to 9.7
III.5	Efficiency of finding kaons in B decays	0.5 per K
III.6	Efficiency of finding protons in B decays	1.0 per p
III.7	Efficiency of particle identifcation based on data control samples	1.5 to 2.5
IV.1	Pdf parameter variation for modes with $D \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, $K\pi\pi$	1.3, 2.8, 5.7, 3.4, resp.
IV.2	Pdf choice for signal events	0.6
IV.3	Pdf choice for background events for $D \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, $K\pi\pi$	0.8, 4.5, 1.3, 2.0, resp.
IV.4	Pdf yield bias by fitting mock experiments embedded with MC	0.4 to 2.2
V.1	Peaking background in $m_{\rm ES}$-ΔE	8.0 for $D^{*0}p\overline{p}\pi$
V.2	Peaking background in $m_{\rm ES}$ only ($D^{(*)0}p\overline{p}\pi\pi$, $K\pi\pi^0$ and $D^{(*)0}p\overline{p}\pi\pi$, $K\pi\pi\pi$)	0.0 to 14.5 (77 to 85)
V.3	Peaking background from identical final states without a D meson	0.5 to 13.5

Theoretical/Phenomenological explanation

- branching fraction results suggest that:
  - multplicity of 4 seems to be preferred
  - two-body baryonic B decays are suppressed
- phenomenological explanation given by:
  - Mahiko Suzuki arXiv:hep-ph/0609133v3



- the gluon has to be highly off mass shell $\rightarrow$ suppressed



- the gluon is close to the mass shell

${}_s\mathcal{P}$lot formalism

- invented for the separation of different event species (N_s)
- define fit function f with components for each species
- fit the distribution in a set of variables $\vec{y}$
- calculate a weight for each event e for species n

$$ {}_s\mathcal{P}_n(\vec{y}_e) = \frac{\sum_{j=1}^{N_s} \mathbf{V}_{nj} f_j(\vec{y}_e)}{\sum_{k=1}^{N_s} N_k f_k(\vec{y}_e)} $$

- $\mathbf{V}$ is the covariance matrix for the yields of the different species
- weights can be used to plot every distribution (not correlated with $\vec{y}$) for each species